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UPDATE OF A FOOTPRINT-BASED APPROACH FOR THE CHARACTERISATION OF COMPLEX MEASUREMENT SITES

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Abstract. Horizontal heterogeneity can significantly affect the flux data quality at monitoring sites in complex terrain. In heterogeneous conditions, the adoption of the eddy-covariance technique is contraindicated by the lack of horizontal homogeneity and presence of advective conditions. In addition, uncertainty concerning the sources or sinks influencing a measurement compromises the data interpretation. The consideration of the spatial context of a measurement, defined by a footprint analysis, can therefore provide an important tool for data quality assessment. This study presents an update of an existing footprint-based quality evaluation concept for flux measurement sites in complex terrain. The most significant modifications in the present version are the use of a forward Lagrangian stochastic trajectory model for the determination of the spatial context of the measurements, and the determination of effective roughness lengths with a flux aggregation model in a pre-processing step. Detailed terrain data gathered by remote sensing methods are included. This approach determines spatial structures in the quality of flux data for varying meteorological conditions. The results help to identify terrain influences affecting the quality of flux data, such as dominating obstacles upwind of the site, or slopes biasing the wind field, so that the most suitable footprint regions for the collection of high-quality datasets can be identified. Additionally, the approach can be used to evaluate the performance of a coordinate rotation procedure, and to check to what extent the measured fluxes are representative for a target land-use type.

Keywords: Complex terrain, Eddy covariance, Flux aggregation, Footprint modelling, Quality assurance, Quality control.

1. Introduction

In order to improve the understanding of the role of different types of ecosystems as sinks or sources for greenhouse gases, the number of flux monitoring stations, organised e.g. in FLUXNET (e.g. Baldocchi et al., 2001),

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has been continuously extended in the last decade or so. At the same time, the focus of these observations has shifted progressively from ideal, homogeneous sites to sites in complex and heterogeneous conditions (e.g. Schmid, 2002). To measure the exchange fluxes between biosphere and atmosphere, most often the eddy-covariance technique is employed (e.g. Aubinet et al., 2000; Baldocchi et al., 2000). However, the adoption of this method in complex terrain potentially violates certain basic theoretical assumptions, such as the need for horizontally homogeneous and steady state flow conditions, and no advection (e.g. Kaimal and Finnigan, 1994; Foken, 2003). In addition, the operation of a flux monitoring station in terrain of variable land-use structure raises the question of which type of vegetation is represented by the measured fluxes.

To address these problems, approaches determining the flux data quality (e.g. Foken and Wichura, 1996) of eddy-covariance measurements should be employed to allow for a profound data interpretation, and the spatial representativeness of the data should be analysed using footprint modelling. Intending to provide a tool for the evaluation of complex measurement sites, Göckede et al. (2004) developed an approach that brings together these two methods; this was successfully applied in an extensive study by Rebmann et al. (2005) to 18 CARBOEUROFLUX sites. Still, their concept suffered some weaknesses that compromised the accuracy of the obtained results.

First of all, the analytic flux source area model (FSAM) of Schmid (1994, 1997) was employed to determine the source area of the measurements. In general, analytical footprint algorithms simplify the actual flow physics in order to gain mathematical simplicity, and thus to decrease the computational expense (Schmid, 2002). Therefore, FSAM is a rather simple model that allows for a fast two-dimensional computation of the source area with reasonable computational expense and satisfying accuracy. However, the model was not designed for operation above tall vegetation, neglecting e.g. within-canopy flow and alongwind diffusion. Secondly, an oversimplified procedure was used to derive a footprint-based roughness length for each 30-min average of the input dataset. This concept considers the composition of land-use types within the source area, but not the structure of the land-use patches, neglecting the requirement for a non-linear flux aggregation to derive an effective value of the roughness length (e.g. Claussen, 1990).

The present study was designed to overcome these two major weaknesses in the approach by Göckede et al. (2004), and thus to improve the accuracy of the site evaluation procedure. First of all, the analytic footprint model FSAM (Schmid, 1994, 1997) was replaced by a forward Lagrangian stochastic (LS) trajectory model (Rannik et al., 2003). This LS model is especially designed to determine the source area over tall vegetation, and considers within-canopy transport processes. Still, even this forward LS model has weak points, such as the assumption of horizontally homogeneous flow conditions, or uncertainties concerning the description of the canopy turbulence, which are treated in more detail in the discussion in Section 7. Concerning the determination of areally-averaged values of the effective roughness length as input for the footprint model, several approaches were tested according to their practicability within the context of the present approach, and for the quality of the results obtained. Finally, the microscale flux aggregation model of Hasager and Jensen (1999) was chosen to compute an individual roughness length for each 30-min average in a pre-processing step. Inputs for this model are a satellite-based land-cover map and the local roughness value in each of the land-cover types. The output is a map of friction velocity in each grid cell calculated as a function of the upwind roughness step changes. With this method, the effective roughness length value can be obtained for larger areas, e.g. the footprint area in our case, using non-linear summation and the assumption of a logarithmic wind profile (Hasager and Jensen, 1999).

Overall, the present approach intends to support the interpretation of results obtained at meteorological sites situated in heterogeneous terrain. Similar to Göckede et al. (2004), it focuses on the visualisation of spatial structures of the quality assessment results of the Foken and Wichura (1996) approach. In this way, the influence of disturbing terrain elements, such as buildings or pronounced hills, on long-term flux measurements will be identified and evaluated, allowing low-quality data to be filtered out. A second major focus is the determination of the average source weight function for a longer measurement period, the so-called ‘footprint climatology’ (e.g. Amiro, 1998). The flux contributions of different types of land-use to the fluxes measured can be evaluated, a feature especially useful for flux monitoring stations in heterogeneous terrain that aim at the examination of a specific type of vegetation. Finally, footprint-averaged mean values of arbitrary input parameters can be calculated, e.g. for the analysis of the vertical wind component, to evaluate the performance of a specific coordinate rotation method.

2. Input Dataset

2.1. Site description and eddy-covariance data

All data used within this study were obtained at the Waldstein Weidenbrunnen site (Gerstberger et al., 2004), which is located in the Fichtelgebirge mountains near Bayreuth, Germany. The flux measurement tower (50°08′31″N, 11°52′01″E, 775 m a.s.l.) has a height of 33 m and is part of the FLUXNET network (Baldocchi et al., 2001). The surrounding terrain is hilly with moderate slopes, mainly covered by spruce forest with a mean tree height of 19 m for the nearest surrounding area. The most important surface heterogeneities affecting the measurements are a large clearing situated approximately 250 m west of the tower, and the summit of the 'Großer Waldstein' (877 m a.s.l.), which lies at a distance of about 1700 m in the south-westerly sector.

The meteorological dataset employed for this analysis covers the period May 21 to July 31, 2003. The eddy-covariance measurement complex consisted of a three-dimensional sonic anemometer (R3, Gill Instruments Ltd., Lymington, U.K.), and an open path infrared gas analyser (LiCor 7500, LI-COR Biosciences, Lincoln, USA). More details on the experimental set-up is provided by Thomas et al. (2004). Signals were stored as 20 Hz raw data, and subsequently processed with a standard procedure for eddy-covariance data including the Planar-Fit coordinate rotation (Wilczak et al., 2001), a spectral correction following Moore (1986), and the WPL correction to account for density fluctuations (Webb et al., 1980; Liebethal and Foken, 2003). In addition, the Foken and Wichura (1996) flux data quality assessment scheme as described in Section 4 is applied.

2.2. Terrain data

A matrix describing the land-use structure of the terrain surrounding the flux tower was produced using satellite remote sensing data. This map, with a horizontal resolution of 15 m, covers an area of 7.1 km in an east–west direction and 5.1 km in a north–south direction. Seven land-use classes were differentiated (Table I), of which the dominant land-use class is conifer, covering more than 60% of the total area. Close to the tower position, the large forested areas are intercepted only by the land-use classes described as clearings (12.3%) and quarry (0.3%); the agricultural land classes surrounding the forest play a marginal role. The assignment of roughness length values to the land-use classes as presented in Table I follows the scheme proposed by Hasager et al. (2002).

3. Methodology on Flux Aggregation

Flux aggregation methods are an important tool used to include subgrid-scale effects into numerical weather prediction, or climate and hydrological modelling (e.g. Mahrt, 1987; Mason, 1988; Claussen, 1991; Mahrt, 1996; Hasager and Jensen, 1999). In heterogeneous terrain, often small-scale variations of surface properties such as temperature, humidity, or aerodynamic roughness, cannot be resolved by the grid cells in these models.

TABLE I

Land-use classes within the observation area at the Waldstein Weidenbrunnen site.

Class	[%] of area	z_0 [m]	Description
Conifer	61.1	1.8	Conifer trees (mainly spruce) of several age classes
Clearings	12.3	0.3	Small open areas with scattered bushes or trees
Grassland	5.6	0.08	Permanent grassland, pasture land
Summer crops	6.5	0.03	Crops with peak in development in late summer
Winter crops	6.2	0.05	Crops with peak in development in early summer
Settlement	4.8	1.2	Rural settlements, buildings, sealed areas
Quarry	0.3	0.5	Area of mining activities
Unclassified	3.2		

The values for the roughness length z_0 are taken from Hasager et al. (2002).

Accordingly, these parameters have to be averaged to provide effective values for the whole grid cell, which allows the production of representative areally-averaged fluxes of momentum, sensible and latent heat, and other scalars (Hasager et al., 2003). By definition, these effective parameters have values that, in homogeneous terrain, would produce fluxes equal to the spatial average found in heterogeneous terrain (Fiedler and Panofsky, 1972; Wieringa, 1986; Mason, 1988; Claussen, 1991).

In the context of footprint studies, aggregation methods have to be employed to provide an effective value of the surface roughness length z_0. In heterogeneous terrain, the roughness length for a specific measurement position might change with the varying source weight function; thus, a suitable method has to be applied to produce an effective z_0 value for each 30-min average of the input dataset.

3.1. Concepts for flux aggregation

An average roughness length value for a heterogeneous grid element can be easily approximated as the arithmetic mean of the individual z_0 values of the patches composing the area. However, this so-called parameter aggregation is physically incorrect (e.g. Claussen, 1990; Foken, 2003), as strong turbulence in small regions can dominate the areally-averaged fluxes (Mahrt, 1987; Schmid and Bünzli, 1995). To account for this non-linearity, several approaches to a flux aggregation method have been developed, with varying degrees of sophistication. One of these is the logarithmic averaging of z_0, which can be further refined to include the apparent friction velocity (e.g. Taylor, 1987; Mason, 1988; Claussen, 1990). Furthermore, the effective z_0 value can be estimated with the drag-law method (Claussen, 1991), which is based on the blending height concept (Wieringa, 1986; Mason, 1988), and the more complex mosaic approach (Avissar and Pielke, 1989; Avissar, 1991).

All aggregation procedures listed above have a common feature, whereby they derive an areally-averaged roughness length taking into account only the composition of land-use types within the specific area. It has been shown from experiment (Klaassen and Claussen, 1995; Flesch and Wilson, 1999; van Breugel et al., 1999; Klaassen et al., 2002) and from theoretical or modelling studies (Schmid and Bünzli, 1995; Mölders et al., 1996; Goode and Belcher, 1999; Hasager and Jensen, 1999) that fluxes in a heterogeneous landscape are not influenced by local surface conditions alone, but also depend on the properties of adjacent areas. This effect is related to internal boundary-layer theory (e.g. Garratt, 1992; Kaimal and Finnigan, 1994). Especially flow across a transition from a smooth to a rough surface leads to an overshoot of turbulence up to a certain downwind distance (Klaassen et al., 2002), such that the average flux of a grid cell can be significantly enhanced in strongly heterogeneous terrain (Friedrichs et al., 2000). Thus, the texture of the surface variability has to be included into the aggregation process in order to avoid an underestimation of the effective roughness length.

Schmid and Bünzli (1995) demonstrated numerically that the stress deviation due to the overshoot of turbulence for a flow across a roughness step-change from smooth to rough surfaces is the dominant process for the areally-averaged fluxes of a heterogeneous grid cell. The first modelling approaches to consider such effects, the so-called subgrid models (Seth et al., 1994; Mölders et al., 1996), were developed as advanced versions of the mosaic approach that do not rearrange the land-use patches within the grid cell. However, high computational resources are required, and because of the scale-dependency of the drag and transfer coefficients (Mahrt and Sun, 1995), the applicability is restricted to scales larger than 4 km (Mölders et al., 1996).

3.2. MICROSCALE AGGREGATION MODEL

A more practicable approach to aggregate roughness lengths under consideration of local advection effects was developed by Hasager and Jensen (1999). This microscale aggregation model takes into account the response of the atmospheric flow for every roughness step change in arbitrary surface conditions. The physics consist of a linearised version of the atmospheric momentum equation in which only the advective term and the vertical flux divergence are assumed to be of importance (Hasager et al., 2003). The algorithms are solved by Fast Fourier Transform (FFT), which allows the time-efficient computation of the effective roughness parameter consistent with the average stress for a given background flow. Terrain information is provided by high resolution two-dimensional land-use maps, with a fixed roughness length assigned to each land-use class. The microscale model allows direct calculation of the effective roughness for the footprint area. The effective roughness varies with wind direction and stability for the specific site. In the context of the site evaluation approach presented, the Hasager and Jensen (1999) microscale aggregation model is used as a pre-processing step to produce tables of effective z_0 values for different flow conditions as input for the footprint model. In the case of the Waldstein Weidenbrunnen site, these tables contain results for 12 wind direction sectors, 14 different settings for the stability of atmospheric stratification, and five temperature regimes in the range $-10\ ^{\circ}\mathrm{C} < T_{\mathrm{air}} < 30\ ^{\circ}\mathrm{C}$. The atmospheric stratification is induced by a temperature difference between the surface temperature T_{surf} and the temperature at measurement height, T_{air}, in the range $-4\,\mathrm{K} < (T_{\mathrm{air}} - T_{\mathrm{surf}}) < 3\,\mathrm{K}$, which corresponds to a stability range of about $-0.25 < z/L < 0.8$, the exact values depending on the temperature regime and the wind direction, with L being the Obukhov length. As the roughness length for more unstable cases was almost constant, model runs for values of z/L below -0.25 were not required.

4. Flux Data Quality Assessment

The quality assessment of the measured fluxes of momentum, sensible and latent heat, and carbon dioxide is performed with a modified version of the method proposed by Foken and Wichura (1996). Individual quality flags are used to rate the stationarity of the data, and to test

TABLE II

Derivation of final quality flags from flags for stationarity and integral turbulence characteristics.

Stationarity flag	1	2	1–2	3–4	1–4	5	≤ 6	≤ 8	≤ 9
Integral turbulence characteristic flag	1–2	1–2	3–4	1–2	3–5	≤ 5	≤ 6	≤ 8	≤ 9
Final flag	1	2	3	4	5	6	7	8	9

Adapted from Foken et al. (2004).

for development of the turbulent flow field with the so-called integral turbulence characteristics. The combination of these two ratings yields the final flux data quality flag (Table II). As no commonly valid integral turbulence characteristics have been developed for the latent heat flux and the CO_2 flux, for the rating of these parameters only the stationarity of the flow and the integral turbulence characteristics of the vertical wind component are considered. Details on the quality flag assignment as well as a discussion on the validity of this approach in complex terrain conditions are presented by Göckede et al. (2004).

5. Source Area Analysis

The footprint analyses are performed with the Thomson (1987) forward LS trajectory model of the Langevin type (e.g. Wilson et al., 1983; Wilson and Sawford, 1996). The exact formulation of the footprint algorithms, including the definition of the flow statistics and the effect of stability on the profiles, can be found in Rannik et al. (2003). The model can be applied to diabatic conditions, and also considers within-canopy flow effects. Like all LS models designed for three-dimensional model domains, the Rannik et al. (2003) model can also treat three-dimensional turbulent diffusion (e.g. Reynolds, 1998). As a forward approach relying on the inverted plume assumption (e.g. Schmid and Oke, 1988; Schmid, 2002), it is restricted to horizontally homogeneous flow conditions. As discussed in more detail in Section 7, this restriction leads to erroneous results of the modelled source area where significant inhomogeneities dominate the flow conditions at the observed site.

For the study presented, the simulations were performed releasing 5×10^4 particles from a height equal to 0.01 times the canopy height [m], which were tracked until the upwind distance accounted for approximately 90% of the total flux. To save computational time, the flux footprint estimators were pre-calculated for any combination of 19 stability classes, 25 roughness lengths, and 22 observation heights, with the definition of the classes independent of the settings for the aggregation model described in Section 3. The number of classes and the range of the parameters were optimised for the analysis of sites enlisted in the CarboEurope-IP project, but can be modified for any site setting if required. This procedure leaves the Obukhov length L, roughness length z_0, and measurement height z_m as the only input parameters required to run the footprint analyses. As the roughness length z_0 required to run the footprint model is derived as a function of atmospheric stability, wind direction ϕ, and air temperature T_{air} [°C] from the results of the aggregation model described in Section 3, ϕ and T_{air} are also needed as input parameters. A test of the influence of a displacement height d for different wind directions on the output of the model revealed a negligible influence of this parameter on the model output for the Waldstein Weidenbrunnen site. The variations of ±0.6 m, which were determined by wind profile evaluations, induced insignificant changes of the averaged flux contribution of the target land-use type (see also Figure 1) in the second decimal place. As the consideration of the effect of varying tree heights on the displacement height for different wind sectors requires a detailed input dataset, this feature is not part of the standard site evaluation procedure, but can be included if the information is available.

To link the meteorological measurements with the terrain information, a footprint analysis was performed for each 30-min average of the observation period. This concept is described in detail by Göckede et al. (2004), and thus is only briefly outlined here. The obtained source weight function was projected onto the land-use matrix by assigning weighting factors ranging from zero to one to all matrix cells. These weighting factors were sorted by the different land-use classes and subsequently summarised, yielding the relative flux contribution of each class to the total flux. This simplified aggregation process is based on the assumption of a uniform flux over all parts of the terrain that have been assigned to the same land-use class.

For the site evaluation concept presented, the individual results of the flux data quality assessment and the footprint analyses had to be combined for the complete observation period. This was obtained by collecting the results for the 30-min average in a database, specifying the individually

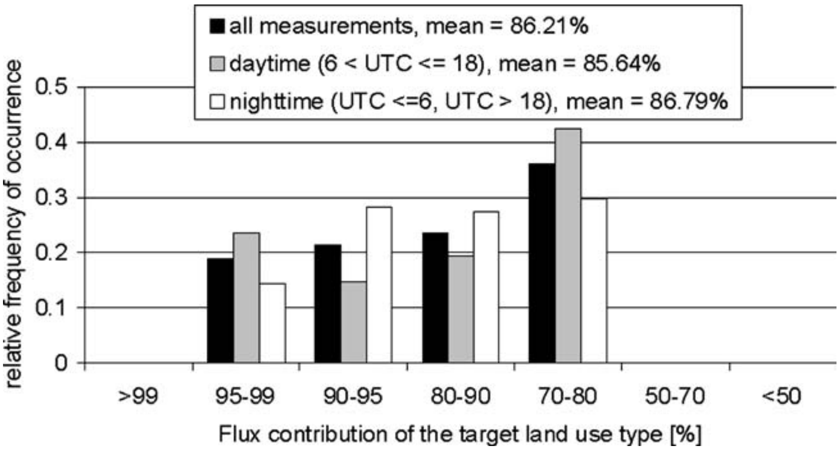

Figure 1. Classified distribution of the relative flux contribution of the target land-use type (spruce forest) to the total flux measured. Frequency distributions were determined for the complete dataset, daytime situations between 0600 and 1800 UTC, and nighttime situations between 1800 and 0600 UTC.

assigned source weight for each matrix cell, as well as the quality flags for each of the five different quantities observed. The quantities considered are momentum flux, sensible heat flux, latent heat flux, CO_2 flux, and the contribution of the land-use type to be observed within the source area to the total flux measured. For the vertical wind component w this procedure was slightly modified. Instead of quality flags, the mean values for w before and after performing the Planar-Fit rotation (Wilczak et al., 2001) were stored in the database.

Finally, for each matrix cell, the entries in the database were evaluated in order to reveal the relative flux contribution to the total flux over the whole observation period, and the mean data quality for each of the six different quantities observed. To obtain the relative flux contribution of a cell, all entered weighting factors were summed and subsequently normalised with the highest sum found in the entire matrix. To assess the overall data quality, the weighting factors were summed for each observed quantity and then sorted according to the quality flag. As the final quality flag for each cell, the median of the distribution of these sums is used. To evaluate the vertical wind speed the arithmetic mean, instead of the median, was computed for each matrix cell of the observed terrain. The results give an overview of the slope of the vertical wind field at the site, and can be used to check the performance of a coordinate rotation procedure, such as the Planar-Fit rotation, by comparing the results before and after the rotation.

6. Results

At most measurement sites, a target land-use type is specified for which the data shall be representative. In the case of heterogeneous terrain, a footprint-based evaluation of the relative flux contribution of the target land-use type to the total flux can help to derive improved results by identifying measurements that are significantly influenced by other types of land-use. These flux contributions can be obtained with the present approach, as shown in a frequency distribution for the Waldstein Weidenbrunnen site during the chosen observation period (Figure 1).

Figure 1 indicates that for the Waldstein Weidenbrunnen site, with an average of about 86%, the flux contribution of the target land-use type (spruce forest) was dominant during the chosen observation period. However, other land-use types (mostly clearings) also had a significant influence, so that if a flux contribution from spruce forest of more than 80% is considered as representative for this type of land-use, only about 64% of the measurements could be used. A differentiation between nighttime and daytime situations included in Figure 1 reveals differences for single flux contribution classes of up to 13% between nighttime and daytime evaluations, while the difference for the mean flux contribution averaged over all measurements is about 1%. The higher average flux contribution during the night, in spite of larger source areas due to the mostly stable atmospheric stratification, can be explained by the dominant south-easterly wind direction, which reduces the influence of the large clearings to the west and to the north of the tower position (see also Figure 2b).

The accumulation of all source weight functions for the 30-min averages of the total observation period yields the so-called 'footprint climatology' for the specific period. In the present approach, this process can also be performed for different stratification regimes, in order to show the varying area of influence on the measurements with changing atmospheric stability. Figure 2 presents examples for unstable stratification (Figure 2a, representing 38% of the input dataset), and stable stratification (Figure 2b, 34% of the dataset), obtained for the Waldstein Weidenbrunnen site.

The white isopleths in Figure 2a and b reproduce the three-dimensional structure of the accumulated source weight function. They indicate the percentage contribution to the total flux, such that all matrix cells lying within the '90'-isopleth have each accumulated flux contributions larger than 90% of the maximum value within the entire matrix. Isopleths below the threshold of 5% are not displayed because of the large areas covered, even though these cells are considered in the evaluations. The figures reveal that, for the chosen observation period at the Waldstein Weidenbrunnen site, during unstable stratification the maximum of the accumulated source weight function is centred at the tower location, while for stable stratification the region to the south-east of the mast was of principal importance

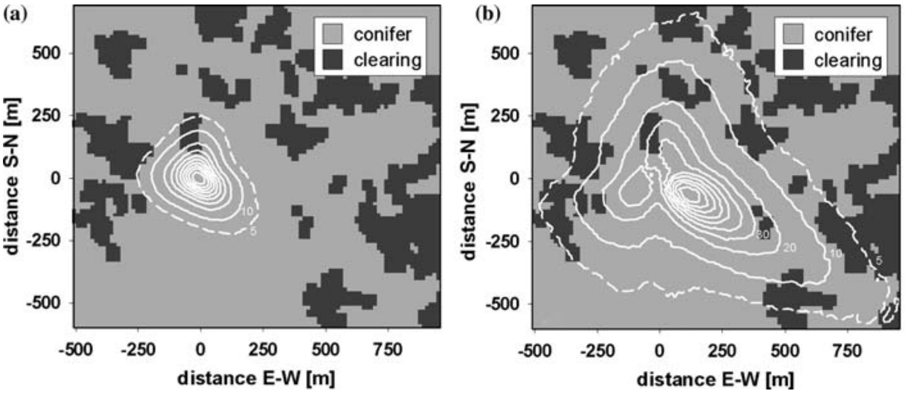

Figure 2. Footprint climatology for the Waldstein Weidenbrunnen site for (a) unstable and (b) stable stratification. The three-dimensional weighting function is indicated by the white lines. Values are in percentages to the peak of the function, with solid lines ranging from 90% to 10%, and the dashed line as 5% of the maximum. Distances to the tower position are given in m, with the tower position located at (0, 0).

for the measurements. For all stratification cases as shown in Figures 4 and 5, the peak of the accumulated source weight function is situated very close to the west of the tower position. The principal part of the fluxes measured under unstable stratification conditions was emitted within an area of about 500 m × 500 m, while for stable stratification the accumulated source weight function has a larger extension of approximately 1400 m × 1200 m.

In order to include a visualisation of the overall data quality of the quantities observed, different greyscales can be used to indicate the results of the data quality assessment. In Figure 3, the greyscales show the dominant data quality flag for the latent heat flux under stable stratification conditions. The white isopleths, specifying the relative flux contributions for the Waldstein Weidenbrunnen site for stable stratification, are included to highlight the region of greatest influence on the observations.

For most parts of the measurement site, the overall rating of the latent heat flux was very good (classes 1–3), indicating that with the employed open path gas analyser, water vapour measurements of high quality can be obtained even in complex terrain. However, the visualisation of the results also reveals two distinct wind sectors with only medium quality (classes 4–6), one in the south and the other in the north-west of the tower position. This reduction of the overall data quality is induced by topographical

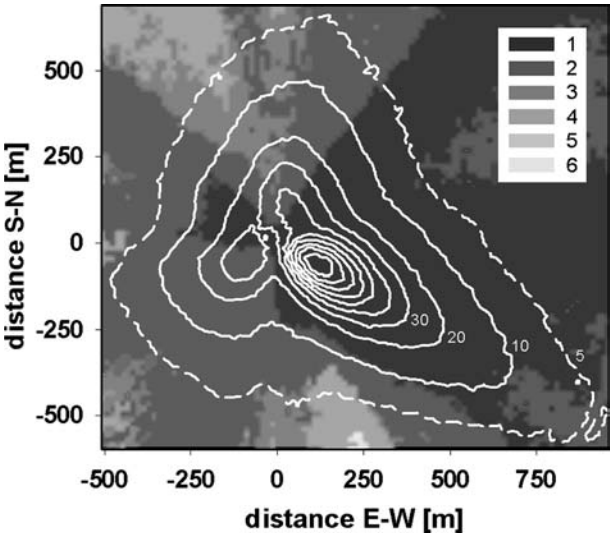

Figure 3. Spatial distribution of the quality assessment results for the latent heat flux during stable stratification. The footprint climatology for stable stratification is indicated by the white isolines. Greyscales indicate the average data quality for each matrix cell. Of the nine possible quality classes ranging from 1 (best) to 9 (worst), only classes 1 to 6 are present in this part of the terrain. Distances to the tower position are given in m, with the tower position located at (0, 0).

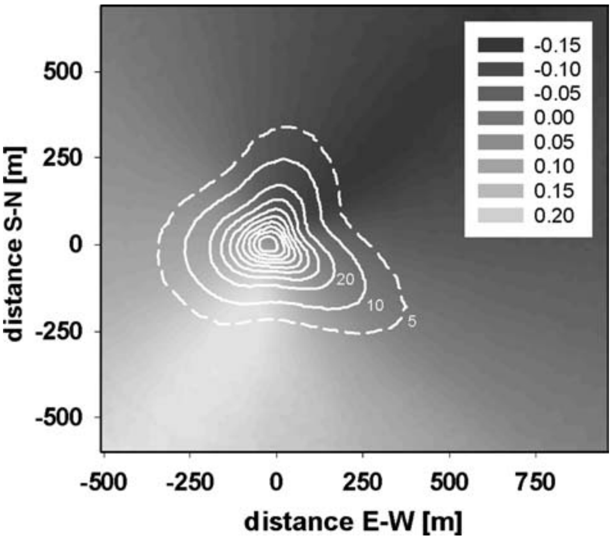

Figure 4. Spatial distribution of the average values of the mean unrotated vertical wind component w. The footprint climatology for all stratification cases is indicated by the white isolines. The greyscales show the mean unrotated w values [m s^{-1}] that have been calculated for each matrix cell under consideration of the footprint results. Distances to the tower position are given in [m], with the tower position located at (0, 0).

effects that disturb the turbulent flow field, as explained in more detail in the following paragraphs.

In addition to the visualisation of spatial structures of quality flags, the present approach can also be employed to produce footprint-averaged maps of other meteorological parameters. Under consideration of the footprint results, a weighted mean value of the specific parameter is computed for each matrix cell, using the entries of the 30-min averages in the database. This method can, for example, be applied to show spatial structures of the vertical wind component w to find out if a rotation method should be applied on the unrotated data, and to check if a possible subsequent coordinate rotation was performed correctly.

In Figure 4, the results for the unrotated values of the mean vertical wind component w at the Waldstein Weidenbrunnen site indicate a general tilt in the wind field, with high positive averaged values of w in the south-westerly wind sector, and a trend for negative values in the north-easterly direction. The slightly higher deviations from zero in the south-westerly wind sector might be caused by the summit of the 'Großer Waldstein', which lies at a distance of about 1700 m in this direction. These results indicate the usefulness of a Planar-Fit coordinate rotation at this site to eliminate the general slope of the wind field induced by the local topography.

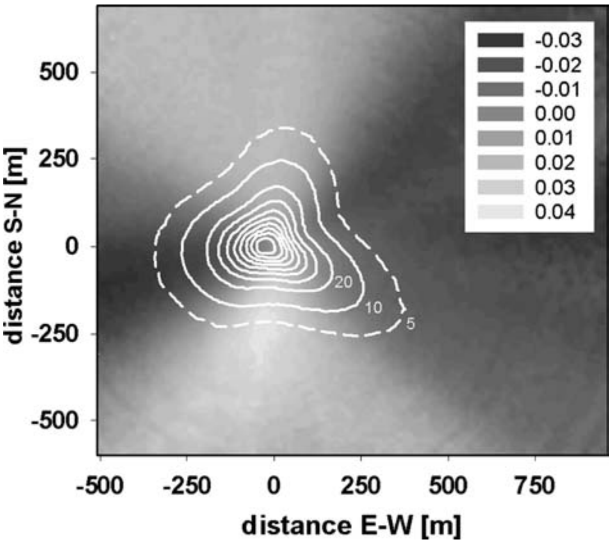

Figure 5. Spatial distribution of the average values of the mean vertical wind component w [m s^{-1}] after performing the Planar-Fit correction. The footprint climatology for all stratification cases is indicated by the white isolines. The greyscales show the mean w values that have been calculated for each matrix cell under consideration of the footprint results. Please note that the range of values is significantly smaller than that shown in Figure 4. Distances to the tower position are given in m, with the tower position located at (0, 0).

The results for the vertical wind component w, after performing the Planar-Fit coordinate rotation shown in Figure 5, demonstrate that the application of this method at the Waldstein Weidenbrunnen site was very effective. Overall, the mean values of w were reduced so that the remaining deviations from zero are insignificant for the computation of the eddy-covariance fluxes. However, this example also demonstrates that even after the rotation, mean values for w may remain where the average wind field is not an even plane, but is instead individually tilted in different wind sectors. The highest deviations shown in Figure 5 are again to be found in the south-westerly sector, and are, again, probably caused by the summit of the 'Großer Waldstein'. The positive deviations found within the northern wind sector may be induced by a steep slope in the topography in this direction. As the residues for w are very small in this case, no further correction is necessary.

7. Discussion

A direct comparison between results obtained by the original method proposed by Göckede et al. (2004) and the revised method, which overcomes

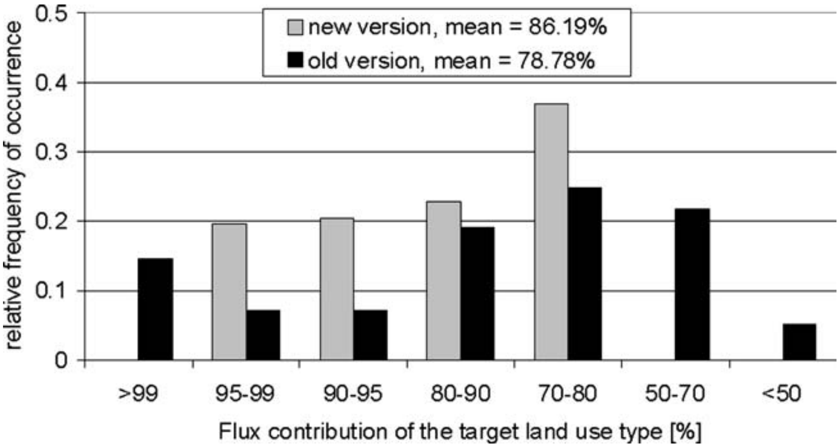

Figure 6. Comparison between results from the analytical version of the approach (Göckede et al., 2004) and from the Lagrangian Stochastic version as presented. The classified distribution of the relative flux contribution of the target land-use type to the total flux measured as computed with the different approaches is shown.

the conceptual weaknesses of the previous version, reveals significant differences (Figure 6).

Similarly to Figure 1, Figure 6 presents the classified flux contributions of the target land-use type for the Waldstein Weidenbrunnen site for the old version of the approach by Göckede et al. (2004) and the new version presented here. As the use of the old version implies that a part of the input dataset is discarded due to model break-ups, for the purpose of comparison, the dataset was also reduced for the new version. Thus, for both versions only about 83% of the available dataset could be used and, as a consequence, the results of the new version deviate slightly from those shown in Figure 1. Figure 6 illustrates the important influence of the improvements implemented in the present approach, with a distinct shift of the frequency distribution towards the higher flux contribution classes for the new version of the approach, and a corresponding increase of the average flux contribution of the target land-use type of about 8%. However, this comparison cannot provide any arguments about which version of the model delivers the better results, as reference values are not available in this example, and the site characteristics do not allow for a thorough model evaluation.

Although some of the main shortcomings of the old version by Göckede et al. (2004) have been improved, the present approach still uses certain simplifications in order to provide a site evaluation tool that is practical and easy to use. As already stated in Section 5, the applied forward LS footprint approach of Rannik et al. (2003) assumes horizontally homogeneous flow. Thus, in principle, the operation of this model is not valid in complex terrain with large step changes in roughness (e.g. Schmid and Oke, 1990), and consequently, the accuracy of the modelling results obtained has to be interpreted with care. However, Foken and Leclerc (2004) presented results for the Waldstein Weidenbrunnen site that demonstrate that even the use of the simpler analytic footprint model by Schmid (1997) could provide valuable information on the characteristics of heterogeneous sites.

As an additional problem, the use of pre-calculated source weight functions does not allow the consideration of site-specific flow statistics; thus, generalisations are required that cause further uncertainty. To eliminate these shortcomings, the adoption of a backward LS model and intensive measurements to adapt it to specific sites would be necessary, making any practical application impossible.

The adoption of the correct flow statistics is a critical task for both analytic and LS footprint models. Since usually no information is available to produce individual velocity statistic profiles for each model run, ensemble-averaged data are used. These profiles, which are averaged over many sampling runs for a specific site, or frequently even taken from observations at other 'representative' sites, do not explicitly resolve the effect of local stability on the flow properties, and the large run-to-run variations in scalar fluxes (Lee, 1998). Hsieh et al. (2003) demonstrate that the adoption of velocity profiles for individual runs did not improve the prediction of within-canopy heat fluxes by a two-dimensional Lagrangian dispersion model. However, this problem emphasises the fact that any footprint model can only be as good as the description of the underlying turbulent flow conditions. The operation of footprint models for flow within or above tall canopies (e.g. Baldocchi, 1997; Rannik et al., 2000, 2003) is compromised, as only few generally valid theories are known for the flow in the canopy space (e.g. Lee, 1998; Finnigan, 2000). Consequently, parameters describing the canopy turbulence, e.g. the profiles of the wind velocity components, have to be approximated with crude generalisations and ad hoc assumptions (Schmid, 2002). Moreover, recent findings by Pyles et al. (2004) demonstrate an influence of the canopy architecture on the directional wind shear within and above tall vegetation, a process that may significantly influence the transport processes, but is not accounted for by most footprint models. In spite of experimental difficulties (e.g. Mahrt, 1998), the problem of transport processes and footprints in and above high vegetation has been analysed in several detailed studies within the last few years (e.g. Lee, 2003; Marcolla et al., 2003; Markkanen et al., 2003). However, to date no unified theoretical framework exists for this type of flow.

A related problem already addressed by Schmid (2002) concerns the treatment of flow affected by step changes in surface properties, e.g. at forest edges or clearings. Such step changes have a significant influence on the atmospheric flow conditions downwind of their position (e.g. Klaassen et al., 2002; Leclerc et al., 2003), as discussed in more detail in Section 3.1. If such inhomogeneities are present, the source of the measured fluxes may significantly deviate from the source area computed by a footprint method that assumes horizontal homogeneous flow (Foken and Leclerc, 2004). In principle, inhomogeneous flow situations can be resolved by backward LS footprint models (Kljun et al., 2002), but a method for an accurate representation of the horizontally heterogeneous statistics as input for the model still has to be developed. Also, the consideration of the topography of the surrounding landscape has not been implemented by existing footprint models to date.

8. Conclusions

A site evaluation approach has been developed that adds to the existing control methods (e.g. Foken et al., 2004) for flux data quality at meteorological measurement sites and flux towers in complex terrain. As an update of the method proposed by Göckede et al. (2004), it combines the results of a quality assessment tool for eddy-covariance measurements (Foken and Wichura, 1996) with a forward Lagrangian stochastic footprint model (Rannik et al., 2003). In a pre-processing step, the microscale flux aggregation model of Hasager and Jensen (1999) is implemented to provide effective roughness lengths as input for the footprint analyses. With no reference available for validation purposes, in spite of partly significant differences to the results obtained with the approach by Göckede et al. (2004), it cannot be proven which of the versions produces the better results. However, as the newly implemented features are better adapted for modelling studies above tall vegetation, it can be assumed that the accuracy of the results was also significantly improved.

The present approach may be applied for the interpretation of results from monitoring stations situated in heterogeneous terrain, e.g. most sites organised in FLUXNET, although it has to be kept in mind that heterogeneous flow conditions are still a problem for models such as those used in the present study. The method yields the dominating quality flag for the different observed fluxes and the relative flux contribution of each cell to the total measured flux. The contribution of the target land-use type to the total flux can be assessed for any user-defined period, indicating how representative the measurements are for that specific kind of surface cover. The approach may also be applied to produce maps of footprint-averaged meteorological parameters such as the vertical wind component w, allowing, e.g., the evaluation of the performance of a coordinate rotation method such as the Planar-Fit approach. Finally, it proves to be a powerful tool for the identification of factors distorting the measurements, such as upwind obstacles, or flow distortion by the instruments themselves, and the visualisation of the effects of these factors on the data quality.

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References

Amiro, B. D.: 1998, 'Footprint Climatologies for Evapotranspiration in a Boreal Catchment', *Agric. For. Meteorol.* **90**, 195–201.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A. S., Martin, P. H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grünwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., and Vesala, T.: 2000, 'Estimates of the Annual Net Carbon and Water Exchange of Forests: The EUROFLUX methodology', *Adv. Ecol. Res.* **30**, 113–175.

Avissar, R. and Pielke, R. A.: 1989, 'A Parameterization of Heterogeneous Land Surfaces for Atmospheric Numerical Models and its Impact on Regional Meteorology', *Mon. Wea. Rev.* **117**, 2113–2136.

Avissar, R.: 1991, 'A Statistical-Dynamical Approach to Parameterize Subgrid-Scale Land-Surface Heterogeneity in Climate Models', *Surv. Geophys.* **12**, 155–178.

Baldocchi, D. D.: 1997, 'Flux Footprints within and over Forest Canopies', *Boundary-Layer Meteorol.* **85**, 273–292.

Baldocchi, D. D., Finnigan, J. J., Wilson, K., Paw U, K. T., and Falge, E.: 2000, 'On Measuring Net Ecosystem Carbon Exchange over Tall Vegetation on Complex Terrain', *Boundary-Layer Meteorol.* **96**, 257–291.

Baldocchi, D. D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Fuentes, J. D., Goldstein, A., Katul, G., Law, B. E., Lee, X., Malhi, Y., Meyers, T., Munger, J. W., Oechel, W., Pilegaard, K., Schmid, H. P., Valentini, R., Verma, S., Vesala, T., Wilson, K., and Wofsy, S.: 2001, 'FLUXNET: A New Tool to Study the Temporal and Spatial Variability of Ecosystem-Scale Carbon dioxide, Water vapour and Energy Flux Densities', *Bull. Amer. Meteorol. Soc.* **82**, 2415–2435.

Claussen, M.: 1990, 'Area-Averaging of Surface Fluxes in a Neutrally Stratified, Horizontally Inhomogeneous Atmospheric Boundary Layer', *Atmos. Environ.* **24A**, 1349–1360.

Claussen, M.: 1991, 'Estimation of Areally-Averaged Surface Fluxes', *Boundary-Layer Meteorol.* **54**, 387–410.

Fiedler, F. and Panofsky, H. A.: 1972, 'The Geostrophic Drag Coefficient and the 'Effective' Roughness Length', *Quart. J. Roy. Meteorol. Soc.* **98**, 213–220.

Finnigan, J. J.: 2000, 'Turbulence in Plant Canopies', *Annu. Rev. Fluid Mech.* **32**, 519–571.

Flesch, T. K. and Wilson, J. D.: 1999, 'Wind and Remnant Tree Sway in Forest Cutblocks. I. Measured Winds in Experimental Cutblocks', *Agric. For. Meteorol.* **93**, 229–242.

Foken, T. and Wichura, B.: 1996, 'Tools for Quality Assessment of Surface-Based Flux Measurements', *Agric. For. Meteorol.* **78**, 83–105.

Foken, T.: 2003, *Angewandte Meteorologie, Mikrometeorologische Methoden*, Springer, Berlin, New York, 289 pp.

Foken, T., Göckede, M., Mauder, M., Mahrt, L., Amiro, B. D., and Munger, J. W.: 2004, 'Post-Field Data Quality Control', in X. Lee, W. J. Massman and B. E. Law (eds), *Handbook of Micrometeorology: A guide for Surface Flux Measurements*, Kluwer Academic Publishers, Dordrecht, pp. 181–208.

Foken, T. and Leclerc, M. Y.: 2004, 'Methods and Limitations in Validation of Footprint Models', *Agric. For. Meteorol.* **127**, 223–234.

Friedrichs, K., Mölders, N., and Tetzlaff, G.: 2000, 'On the Influence of Surface Heterogeneity on the Bowen-ratio: A Theoretical Case Study', *Theor. Appl. Climatol.* **65**, 181–196.

Garratt, J. R.: 1992, *The Atmospheric Boundary Layer*, Cambridge University Press, Cambridge, 316 pp.

Gerstberger, P., Foken, T., and Kalbitz, K.: 2004, 'The Lehstenbach and Steinkreuz Catchments in NE Bavaria, Germany', in E. Matzner (ed.), *Biogeochemistry of Forested Catchments in a Changing Environment, Ecological Studies, Vol. 172*, Springer, Berlin, New York, pp. 15–44.

Göckede, M., Rebmann, C., and Foken, T.: 2004, 'A Combination of Quality Assessment Tools for Eddy Covariance Measurements with Footprint Modelling for the Characterisation of Complex Sites', *Agric. For. Meteorol.* **127**, 175–188.

Goode, K. and Belcher, S. E.: 1999, 'On the Parameterisation of the Effective Roughness Length for Momentum Transfer over Heterogeneous Terrain', *Boundary-Layer Meteorol.* **93**, 133–154.

Hasager, C. B. and Jensen, N. O.: 1999, 'Surface-Flux Aggregation in Heterogeneous Terrain', *Quart. J. Roy. Meteorol. Soc.* **125**, 2075–2102.

Hasager, C. B., Nielsen, N. W., Soegaard, H., Boegh, E., Christensen, J. H., Jensen, N. O., Schultz Rasmussen, M., Astrup, P., and Dellwik, E.: 2002, *SAT-MAP-CLIMATE Project results*, Risö National Laboratory, Roskilde, 71 pp.

Hasager, C. B., Nielsen, N. W., Jensen, N. O., Boegh, E., Christensen, J. H., Dellwik, E., and Soegaard, H.: 2003, 'Effective Roughness Calculated from Satellite-Derived Land Cover Maps and Hedge-Information used in a Weather Forecasting Model', *Boundary-Layer Meteorol.* **109**, 227–254.

Hsieh, C. I., Siqueira, M., Katul, G., and Chu, C. R.: 2003, 'Predicting scalar source–sink and flux distributions within a forest canopy using a 2-D Lagrangian stochastic dispersion model', *Boundary-Layer Meteorol.* **109**, 113–138.

Kaimal, J. C. and Finnigan, J. J.: 1994, *Atmospheric Boundary Layer Flows: Their Structure and Measurement*, Oxford University Press, New York, 289 pp.

Klaassen, W. and Claussen, M.: 1995, 'Landscape Variability and Surface Flux Parameterization in Climate Models', *Agric. For. Meteorol.* **73**, 181–188.

Klaassen, W., van Breugel, P. B., Moors, E. J., and Nieveen, J. P.: 2002, 'Increased Heat Fluxes near a Forest Edge', *Theor. Appl. Climatol.* **72**, 231–243.

Kljun, N., Rotach, M. W., and Schmid, H. P.: 2002, 'A Three-Dimensional Backward Lagrangian Footprint Model for a Wide Range of Boundary-Layer Stratifications', *Boundary-Layer Meteorol.* **103**, 205–226.

Leclerc, M. Y., Karipot, A., Prabha, T., Allwine, G., Lamb, B., and Gholz, H. L.: 2003, 'Impact of Non-Local Advection on Flux Footprints over a Tall Forest Canopy: a Tracer Flux Experiment', *Agric. For. Meteorol.* **115**, 19–30.

Lee, X.: 1998, 'On Micrometeorological Observations of Surface-Air Exchange Over Tall Vegetation', *Agric. For. Meteorol.* **91**, 39–49.

Lee, X.: 2003, 'Fetch and Footprint of Turbulent Fluxes Over Vegetative Stands with Elevated Sources', *Boundary-Layer Meteorol.* **107**, 561–579.

Liebethal, C. and Foken, T.: 2003, 'On the Significance of the Webb Correction to Fluxes', *Boundary-Layer Meteorol.* **109**, 99–106.

Mahrt, L.: 1987, 'Grid-Averaged Surface Fluxes', *Mon. Wea. Rev.* **115**, 1550–1560.

Mahrt, L. and Sun, J. L.: 1995, 'Dependence of Surface Exchange Coefficients on Averaging Scale and Grid Size', *Quart. J. Roy. Meteorol. Soc.* **121**, 1835–1852.

Mahrt, L.: 1996, 'The Bulk Aerodynamic Formulation over Heterogeneous Surfaces', *Boundary-Layer Meteorol.* **89**, 87–119.

Mahrt, L.: 1998, 'Flux Sampling Errors for Aircraft and Towers', *J. Atmos. Ocean. Technol.* **15**, 416–429.

Marcolla, B., Pitacco, A., and Cescatti, A.: 2003, 'Canopy Architecture and Turbulence Structure in a Coniferous Forest', *Boundary-Layer Meteorol.* **108**, 39–59.

Markkanen, T., Rannik, Ü., Marcolla, B., Cescatti, A., and Vesala, T.: 2003, 'Footprints and Fetches for Fluxes over Forest Canopies with Varying Structure and Density', *Boundary-Layer Meteorol.* **106**, 437–459.

Mason, P. J.: 1988, 'The Formation of Areally-Averaged Roughness Lengths', *Quart. J. Roy. Meteorol. Soc.* **114**, 399–420.

Mölders, N., Raabe, A., and Tetzlaff, G.: 1996, 'A Comparison of Two Strategies on Land Surface Heterogeneity used in a Mesoscale Beta Meteorological Model', *Tellus A* **48**, 733–749.

Moore, C. J.: 1986, 'Frequency Response Corrections for Eddy Correlation Systems', *Boundary-Layer Meteorol.* **37**, 17–35.

Pyles, R. D., Paw U, K. T., and Falk, M.: 2004, 'Directional Wind Shear within an Old-Growth Temperate Rainforest: Observations and Model Results', *Agric. For. Meteorol.* **125**, 19–31.

Rannik, Ü., Aubinet, M., Kurbanmuradov, O., Sabelfeld, K. K., Markkanen, T., and Vesala, T.: 2000, 'Footprint Analysis for Measurements over a Heterogeneous Forest', *Boundary-Layer Meteorol.* **97**, 137–166.

Rannik, Ü., Markkanen, T., Raittila, J., Hari, P., and Vesala, T.: 2003, 'Turbulence Statistics Inside and Over Forest: Influence on Footprint Prediction', *Boundary-Layer Meteorol.* **109**, 163–189.

Rebmann, C., Göckede, M., Foken, T., Aubinet, M., Aurela, M., Berbigier, P., Bernhofer, C., Buchmann, N., Carrara, A., Cescatti, A., Ceulemans, R., Clement, R., Elbers, J. A., Granier, A., Grünwald, T., Guyon, D., Havránková, K., Heinesch, B., Knohl, A., Laurila, T., Longdoz, B., Marcolla, B., Markkanen, T., Miglietta, F., Moncrieff, J. B., Montagnani, L., Moors, E., Nardino, M., Ourcival, J.-M., Rambal, S., Rannik, Ü., Rotenberg, E., Sedlak, P., Unterhuber, G., Vesala, T. and Yakir, D.: 2005, 'Quality Analysis Applied on Eddy Covariance Measurements at Complex Forest Sites using Footprint Modelling', *Theor. Appl. Climatol.* **80**, 121–141.

Reynolds, A. M.: 1998, 'A Two-Dimensional Lagrangian Stochastic Dispersion Model for Convective Boundary Layers with Wind Shear', *Boundary-Layer Meteorol.* **86**, 345–352.

Schmid, H. P. and Oke, T. R.: 1988, 'Estimating the Source Area of a Turbulent Flux Measurement over a Patchy Surface', *in* 8^{th} *Symposium on Turbulence and Diffusion*, Boston, MA, American Meteorological Society, pp. 123–126.

Schmid, H. P. and Oke, T. R.: 1990, 'A Model to Estimate the Source Area Contributing to Turbulent Exchange in the Surface Layer Over Patchy Terrain', *Quart. J. Roy. Meteorol. Soc.* **116**, 965–988.

Schmid, H. P.: 1994, 'Source Areas for Scalars and Scalar Fluxes', *Boundary-Layer Meteorol.* **67**, 293–318.

Schmid, H. P. and Bünzli, D.: 1995, 'The Influence of Surface Texture on the Effective Roughness Length', *Quart. J. Roy. Meteorol. Soc.* **121**, 1–21.

Schmid, H. P.: 1997, 'Experimental Design for Flux Measurements: Matching Scales of Observations and Fluxes', *Agric. For. Meteorol.* **87**, 179–200.

Schmid, H. P.: 2002, 'Footprint Modeling for Vegetation Atmosphere Exchange Studies: A Review and Perspective', *Agric. For. Meteorol.* **113**, 159–183.

Seth, A., Giorgi, F., and Dickinson, R. E.: 1994, 'Simulating Fluxes from Heterogeneous Land Surfaces: Explicit Subgrid Method Employing the Biosphere-Atmosphere Transfer Scheme (BATS)', *J. Geophys. Res.-Atmos.* **99**, 18651–18667.

Taylor, P. A.: 1987, 'Comments and Further Analysis on Effective Roughness Lengths for use in Numerical Three-Dimensional Models', *Boundary-Layer Meteorol.* **39**, 403–418.

Thomas, C., Ruppert, J., Lüers, J., Schröter, J., Mayer, J. C., and Bertolini, T.: 2004, Documentation of the WALDATEM-2003 Experiment. Universität Bayreuth, Abteilung Mikrometeorologie, Arbeitsergebnisse, Print ISSN 1614-8916, No. 24, 59 pp.

Thomson, D. J.: 1987, 'Criteria for the Selection of Stochastic Models of Particle Trajectories in Turbulent Flows', *J. Fluid Mech.* **180**, 529–556.

van Breugel, P. B., Klaassen, W., and Moors, E. J.: 1999, 'Fetch Requirements near a Forest Edge', *Phys. Chem. Earth Pt. B* **24**, 125–131.

Webb, E. K., Pearman, G. I., and Leuning, R.: 1980, 'Correction of Flux Measurements for Density Effects due to Heat and Water Vapour Transfer', *Quart. J. Roy. Meteorol. Soc.* **106**, 85–100.

Wieringa, J.: 1986, 'Roughness-Dependent Geographical Interpolation of Surface Wind Speed Averages', *Quart. J. Roy. Meteorol. Soc.* **112**, 867–889.

Wilczak, J. M., Oncley, S. P., and Stage, S. A.: 2001, 'Sonic Anemometer Tilt Correction Algorithms', *Boundary-Layer Meteorol.* **99**, 127–150.

Wilson, J. D., Legg, B. J., and Thomson, D. J.: 1983, 'Calculation of Particle Trajectories in the Presence of a Gradient in Turbulent-Velocity Variance', *Boundary-Layer Meteorol.* **27**, 163–169.

Wilson, J. D. and Sawford, B. L.: 1996, 'Review of Lagrangian Stochastic Models for Trajectories in the Turbulent Atmosphere', *Boundary-Layer Meteorol.* **78**, 191–210.